Integral Field Spectroscopy of a peculiar Supernova Remnant MF16 in NGC6946

Abolmasov P.^{1,2} Fabrika S.², Sholukhova O.² and Afanasiev V.²

- ¹ Moscow State University
- ² Special Astrophysical Observatory RAS

Summary. We present a study of a peculiar Supernova Remnant MF16, associated with the Ultraluminous X-ray Source (ULX) NGC6946 ULX-1. Observations were taken with the MultiPupil Fiber Spectrograph (MPFS) with the 6-m telescope on January 2005. The nebula is found to be highly asymmetric, one of the parts being much denser and colder. Two-component structure of the emission lines and radial velocity gradient in some of them argue for a non-spherical nebula, expanding with a velocity of about $100km\,s^{-1}$. Neither shock models nor the X-ray emission can adequately explain the actual emission line spectrum of MF16, so we suggest an additional ultraviolet source with a luminosity of about $10^{40}erg\,s^{-1}$. We confirm coincidence of the ULX with the central star, and identify radio emission observed by VLA with the most dense part of the nebula.

Introduction

The attention to MF16 was first drawn by Blair & Fesen [1], who identified the object as a Supernova Remnant (SNR), according to the emission-line spectrum with bright collisionally-excited lines. It was long considered as a peculiar and unusually luminous SNR, because of its huge optical emission-line ($L_{H\alpha} = 1.9 \times 10^{39} erg \, s^{-1}$, according to [1], for the tangential size $20 \times 34pc$) and X-ray ($L_X = 2.5 \times 10^{39} erg \, s^{-1}$ in the 0.5 - 8 keV range, according to [2]) luminosities.

However, it was shown by Roberts & Colbert [2] that the spectral, spatial and timing properties of the X-ray source do not agree with the suggestion of a bright SNR, but rather suppose a point source with a typical "ULX-like" X-ray spectrum: cool Multicolor Disk (MCD) and a Power Law (PL) component. So, apart from the physical nature of the object, MF16 should be considered a *ULX nebula*, one of a new class of objects, described by Pakull & Mirioni, [3]. For introduction into ULX-counterparts see [4].

Observations and Data Reduction

We analyse spectra obtained with the SAO 6m telescope using Multipupil Fiber Spectrograph (MPFS, [6]), with a spectral resolution $\Delta\lambda \simeq 8\mathring{A}$ in $4000-7000\mathring{A}$ spectral range. MPFS field consists of $16\times16~1''\times1''$ spaxels.

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For the nebula size (in its brightest part) $1'' \times 1.''5$ it means rather poor spatial resolution, yet one can resolve the structure of the object, considering offset pixels, were the PSF wings of the closest parts of the nebula contribute.

Data reduction system was written in IDL environment, using procedures, written by V. Afanasiev, A. Moiseev and P. Abolmasov. We also added atmospheric dispersion correction in order to culculate correctly the nebula barycenters.

Results

More complete version of the results will be published in [7]. Integral fluxes, velocities, FWHMs and barycenters for selected lines are listed in Table 1. The integral unreddened flux in H_{β} line is $F_{H\beta} = (2.00 \pm 0.06) 10^{-14} erg \ cm^{-2} s^{-1}$. Assuming $H_{\alpha}/H_{\beta} = 3$ we find interstellar absorption $A_V = 1.^m 24$. Unreddening was produced using Cardelli et al. [5] algorythm. In the Table 1 we present the most important parameters of selected emission lines, including barycenter shifts versus *Chandra* source coordinates [2]. An interesting result can be seen that the barycenter is shifted to the West for low-excitation lines (Balmer lines, [SII], [OI]), and to the East for the most high-excitation line HeII λ 4686. That can be understood as a global physical conditions gradient: the western part of MF16 is denser and colder than the eastern.

Table 1. MF16 selected emission line properties.

line	$F(\lambda)/F(H_{\beta})$	$F(\lambda)/F(H_{\beta})$ (unreddened)		FWHM, Å	$\Delta \alpha_c, arcsec$	$\Delta \delta_c, arcsec$
=		(unreddened)				
$HeII\lambda 4686$	$0.20 {\pm} 0.03$	$0.22 {\pm} 0.03$	-5±18	$6.8 {\pm} 0.7$	$0.302 {\pm} 0.05$	0.146 ± 0.03
H_{eta}	1.00 ± 0.03	1.00 ± 0.03	-28 ± 4	7.0 ± 0.2	-0.11 ± 0.02	-0.10 ± 0.02
$[OIII]\lambda 5007$	$7.42 {\pm} 0.15$	$6.94 {\pm} 0.14$	-17 ± 2	$6.7 {\pm} 0.1$	$0.058{\pm}0.015$	0.011 ± 0.015
$[OI]\lambda 6300$	$1.42 {\pm} 0.08$	$0.93 {\pm} 0.05$	25 ± 9	$10.1 {\pm} 0.4$	-0.196 ± 0.015	-0.237 ± 0.015
H_{α}	4.73 ± 0.09	2.96 ± 0.06	-16 ± 2	7.8 ± 0.1	-0.111 ± 0.013	-0.08 ± 0.013
$[NII]\lambda6583$	$4.16 {\pm} 0.08$	$2.59 {\pm} 0.05$	-19 ± 2	$7.6 {\pm} 0.1$	-0.061 ± 0.013	-0.064 ± 0.013
$[SII]\lambda 6717$	$2.46{\pm}0.02$	$1.496{\pm}0.015$	-37.5 ± 1.1	$7.7 {\pm} 0.1$	-0.116 ± 0.014	-0.081 ± 0.014

For some of the line profiles, that seem to have distinct two-component structure, we also produce two-gaussian fit (see Table 2). The velocity shift between the line components is about $120km \, s^{-1}$ for all the lines resolved into two components. This value is consistent with the velocity gradient seen for $[OIII]\lambda 5007$ line, exceeding $50km \, s^{-1}$ [7] and directed along the major axis of the nebula. Recent observations with higher spectral resolution [8] confirm the result, that the nebula expands with either ~ 120 (if we suggest just one

Table 2. MF16 two-component emission lines properties

$\lambda, m \AA$	$F_1(\lambda)/F(H_\beta)$	$V_1, km/s$	$FWHM_1, Å$	$F_2(\lambda)/F(H_\beta)$	$V_2, km/s$	$FWHM_2, Å$
$HeII\lambda 4686$	0.107 ± 0.007	$\text{-}142 {\pm} 20$	$11.6 {\pm} 0.6$	0.093 ± 0.004	$10.\pm 5.$	$4.26{\pm}0.15$
H_{β}	$0.424{\pm}0.037$	$\text{-}122 \!\pm\! 17$	10.24 ± 0.50	$0.58 {\pm} 0.02$	-2 ± 5	$5.67 {\pm} 0.16$
$[OIII]\lambda 4959$	$0.875 {\pm} 0.014$	-122 ± 3	$8.5 {\pm} 0.1$	$1.486 {\pm} 0.012$	8 ± 1	5.78 ± 0.12
$[OIII]\lambda 5007$	$2.696 {\pm} 0.015$	-115 ± 1	8.77 ± 0.04	$4.455{\pm}0.012$	11 ± 2	$5.63 {\pm} 0.05$

shock wave with precursor), or $\sim 60km\,s^{-1}$ (if we see the both receding and approaching parts of the nebula) velocity. In all the profiles the blue components are significantly broader, corresponding to velocity dispersion $300-400km\,s^{-1}$.

Having the spectral line fluxes and kinematics, one can judge about the nature of the nebula. It is well-known [10, 2] that the optical emission-line luminosity of MF16 exceeds very much that of a SNR with comparable size, so one should suggest either a more powerful shock or an additional photoionizing source. If we consider a pure shock-wave excitation, the H_{β} flux density will be connected to the shock parameters as was stated by Dopita & Sutherland [11]:

$$F_{H\beta} = F_{H\beta,shock} + F_{H\beta,precursor} = 7.44 \times 10^{-6} \left(\frac{V_s}{100km \, s^{-1}}\right)^{2.41} \times \left(\frac{n_2}{cm^{-3}}\right) + 9.86 \times 10^{-6} \left(\frac{V_s}{100km \, s^{-1}}\right)^{2.28} \times \left(\frac{n_1}{cm^{-3}}\right) \, erg \, cm^{-2} s^{-1}$$

Here n_1 and n_2 are pre- and postshock number densisties, correspondingly. Basing on this formula and assuming the nebula a sphere with 13pc radius, and $n_2 \simeq 500cm^{-3}$ [10] one can see the potential shock velocity varies from $150km \, s^{-1}$ (for $n_1 = 100cm^{-3}$, adiabatic shock) up to $350km \, s^{-1}$ (for $n_1 \to 0cm^{-3}$, fully radiative shock).

High-excitation lines

[OIII] and HeII lines in MF16 appear to be unusually bright for a shock-ionized nebula. Observed ratio of [OIII] $\lambda 5007$ / H_{β} \sim 7 requires a shock velocity about $400km\,s^{-1}$ [12]. As for HeII / H_{β} \sim 0.2 value, it cannot be explained by existing shock+precursor models [12, 11]

HeII ionization suggests a quite specific photoionizing source – extreme ultraviolet (EUV) with $\lambda < 228 \text{\AA}$. An estimate of the EUV luminosity can be made using ionizing quanta number estimate [13]:

$$L_{\lambda < 228 \mathring{A}} \ge \frac{E_{UV}}{E_{\lambda 4686}} \frac{\alpha_B}{\alpha_{HeII \,\lambda 4686}^{eff}} \times L_{HeII \,\lambda 4686} \simeq 10^{39} erg \, s^{-1}$$

Photoionization Modelling

We have computed a grid of CLOUDY96.01 [14] photoionization models in order to fit MF16 spectrum avoiding shock waves. We have fixed X-ray spectrum known from Chanrda observations [2] assuming all the plasma is located at 10pc from the central point source, and introduced a blackbody source with the temperature changing from 10^3 to 10^6 K and integral flux densities from 0.01 to $100~erg~cm^{-2}~s^{-1}$.

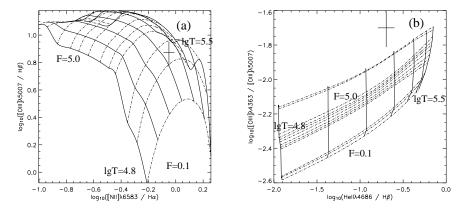


Fig. 1. $[OIII]\lambda5007/H_{\beta}$ versus $[NII]\lambda6583/H_{\alpha}$ (a) and $HeII\lambda4686/H_{\beta}$ versus $[OIII]\lambda4363/[OIII]\lambda5007$ (b) ionization diagrams with the integral spectrum of MF16 shown by a cross of error bars. Photoionization grid descibed in the text is also shown. Solid lines trace the constant temperature levels, dot-dashed lines correspond to constant black body flux densities. Only models with $\lg T(K) = 4.80 - 5.30$ and $F = 0.1 - 7.0erg~cm^{-2}~s^{-1}$ are shown.

The best fit parameters are $\lg T(K) = 5.15 \pm 0.05$, $F = 0.6 \pm 0.1 erg \, cm^{-2} \, s^{-1}$, that suggests quite a luminous ultraviolet source: $L_{UV} = (7.5 \pm 0.5) \times 10^{39} erg \, s^{-1}$. More completely the modelling results and methodics will be presented in [8]. The UV source is more than 100 times brighter then what can be predicted by extrapolating the best-fit model for X-ray data [2].

Conclusions

MF16 has a nontrivial emission line spectrum, similar to those observed in NLRs of Seyfert galaxies. The nebula is highly asymmetric, with a dense cold western part, possibly connected with the radio-bright region [15]. Kinematical properties suggest an expanding non-spherical shell. The sources of ionization acting in different parts of the nebula are probably different, strong ra-

diative shock at the western end and in the outer regions, and hard UV/EUV radiation source in the inner/eastern regions.

Basing on the HeII4686 luminosity we should suggest a $\sim 10^{39} erg \, s^{-1}$ EUV ($\lambda \leq 228 \text{Å}$) source responsible for the second ionization of He. CLOUDY simulations suggest a $L_{UV} \sim 10^{40} erg \, s^{-1}$ FUV luminosity needed to produce the actual [OIII] $\lambda 5007 / H_{\beta}$ ratio.

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